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OIL-FREE TURBOMACHINERY TECHNOLOGY FOR REGIONAL JET, ROTORCRAFT AND SUPERSONIC BUSINESS JET PROPULSION ENGINES

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Abstract

Recent breakthroughs in Oil-Free technologies (foil air bearings, high temperature tribological coatings and computer based modeling) have created resurgence in research to develop Oil-Free turbomachinery systems. Foil bearings are hydrodynamic, self acting fluid film bearings which use air as their working fluid or lubricant and require no external pressurization. The fluid film is formed between the moving shaft surface and a flexible sheet metal foil which is, in turn, supported by a series of spring foils which provide compliance. The compliant characteristics accommodate misalignment and distortion and allow for micro-sliding between foil layers which gives the bearing coulomb damping. When coupled with new high temperature solid lubricant coatings for startup and shutdown wear protection, these bearings can and do operate from cryogenic temperatures to over 650 C. These positive attributes have led to many commercial applications benefiting from high reliability, low friction, and long life performance.

For over three decades Oil-Free turbomachinery has been fully commercialized in Air Cycle Machines (ACM)'s used for aircraft cabin pressurization. These turbomachines operate at moderate temperatures, loads and speeds and utilize fairly simple foil air bearing designs and conventional polymer solid lubricant coating technology. During the 1970's, foil bearing technology improved to the point that load capacities were sufficient to support high speed cryogenic turbopump and compressor systems. This was accomplished through the improvement of bearing load capacity through the tailoring of the elastic support structure to maximize the air film thickness and the development of improved polymer solid lubricants. More recently, breakthroughs in computer based hydrodynamic gas film and finite element structural modeling has resulted in foil bearing load capacities more than double previously attained levels. In early 1999, advanced foil bearings, new NASA developed high temperature coatings and modeling was used to successfully demonstrate the world's first Oil-Free turbocharger for a heavy duty diesel truck engine. The Oil-Free turbocharger operates at 95,000 rpm at temperatures to 650 C and produces 150 hp. This experience, coupled with further advances in bearings and high temperature solid lubricants has enabled Oil-Free technology to move into gas turbine engines.

In late 1999, the first commercially available Oil-Free gas turbine based (microturbine) electrical generators entered the market. To date, well over 2500 of these small (30-60 kW) units are in operation and larger units (up to 400 kW) are being developed. These products take advantage of the low

cost, no maintenance and low friction benefits that foil bearings provide. In addition, the elimination of oil lubrication significantly reduces system complexity, weight and parts count as well as allowing operation at bearing temperatures to 650 C minimizing the need for cooling. These microturbines also represent a significant step forward for Oil-Free turbomachinery technology demonstrating the successful transition from power absorbing compression machines to power producing heat engines. Further advances in bearings, tribological coatings and component and system modeling and integration now enable additional transition of the technology to propulsion turbine engines.

An ongoing research project at NASA Glenn is the demonstration of a 700 pound thrust, Oil-Free turbofan engine for a small subsonic business jet. This project builds upon the technology advances in foil bearings, coatings and modeling and will be the first Oil-Free, man rated propulsion engine demonstrated. It is estimated that the integration of Oil-Free technologies in aircraft engines will result in a weight reduction of approximately 15%, a 20% power density increase, a 50% maintenance cost reduction and an 8% Direct Operating Cost (DOC) reduction. Recent technology performance data has resulted in validated bearing performance models which indicate that larger bearing sizes are achievable opening the possibility of supporting larger and more complex engines in the future. This paper introduces the Oil-Free technologies, their state of development, capability and limitations and considers their application to Regional Jet, Rotorcraft and Supersonic Business jet engines.

Introduction

Oil lubrication has played a vital role in aircraft propulsion engines since the Wright brothers flew at Kitty Hawk a century ago. Oil provides both a lubrication effect as well as critical cooling for key internal engine structures. Without oil lubrication system technology our aviation industry would not have been able to get off the ground. The oil lubrication system, however, has also imparted significant engineering limitations on aircraft propulsion engines which have shaped current technology and is constraining major improvements in future engines(1).

For instance, despite dedicated research over the past thirty years, turbine oil cannot operate over 350 F necessitating designs encumbered with oil coolers, filters and temperature sensors and seals. In addition, oil lubricated ball and roller bearings, found in all aircraft engines, suffer from the effects of centrifugal loading at high speeds (DN values) which imposes limits on shaft diameter, and hence stiffness, and shaft speed(2). Further, since the bearing system can be viewed as the foundation upon which the engine rotor is built, its strengths and weaknesses significantly influence engine design and performance.

Today’s engine bearing systems are largely the same as those of three decades ago. As a consequence, today’s engines are, in many respects, similar to previous designs. Performance improvements have predominantly been achieved through higher operating temperature alloys and cooling methods and the increased reliance on high bypass ratio fans. Following this technological development path, today’s engine technology is quite mature and investments to further improve performance can yield only modest gains. In order to dramatically improve aircraft propulsion systems, the technology used for the very foundation, the shaft support and lubrication system must be fundamentally changed. By changing the rotor support system new opportunities are created to allow innovative turbomachinery design and operation enabling revolutionary performance benefits.

This paper describes research to combine three key technologies; foil air bearings, high temperature solid lubricants and computer based modeling and system integration into Oil-Free Turbomachinery based engines. These advanced engines offer dramatic improvements in performance and efficiency and have the potential to revolutionize aircraft design and operation.

Technology Background:

Foil Air Bearings

Foil bearings were first described in a paper by Blok and Van Rossum in 1953(3). Their simple bearing was formed by a strip of cellophane tape draped over a spinning shaft and was lubricated with oil. This concept was adopted by investigators studying magnetic recording tape transport phenomena. Their observations that a lubricating air film formed between magnetic tape and high speed drive spindles led to the development of the first air lubricated foil bearings(4). Modern foil bearings consist of a series of sheet metal foil layers which are wrapped around a rotating shaft. The innermost foil layer traps the hydrodynamic air film which supports the shaft load. The underlying foil layers act as support springs offering compliance and coulomb damping to the bearing (5).

Early foil bearing designs were simple like those shown in figures 1 and 2 (6, 7). These Generation I bearings developed load capacities comparable to rigid gas bearings with the added benefits of misalignment tolerance, damping and accommodation of centrifugal and thermal shaft distortions. Generation I bearings were commercialized in small, lightly load turbomachinery (i.e., air cycle machines or ACM's) but had insufficient load capacity for larger, more demanding applications (6).

In the 1980's, new bearing designs emerged, designated Generation II, which incorporated a more complex spring support structure (8). In these bearings, the elastic stiffness of the support springs is tailored in one direction, typically axially, to accommodate for hydrodynamic effect such as edge leakage. Figure 3 shows this type of bearing which exhibits load capacities nearly double more primitive Generation I designs. The Generation II bearings enabled new more challenging Oil-Free

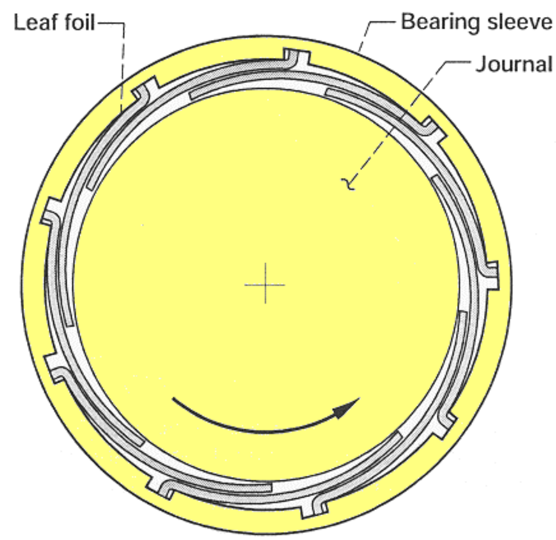

Figure 1 – Generation I leaf style foil bearing

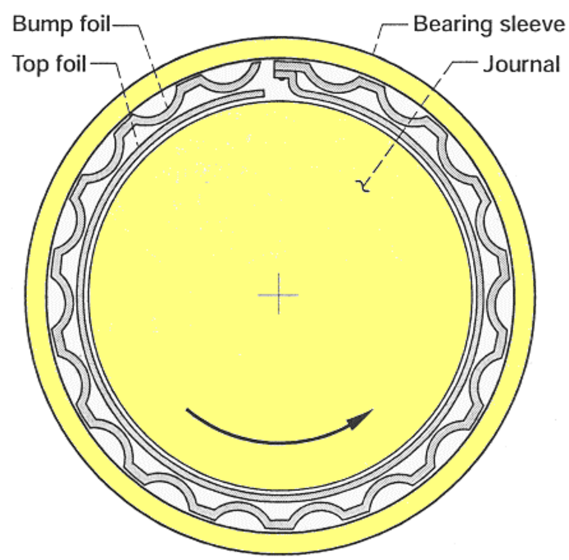

Figure 2 – Generation I bump style foil bearing

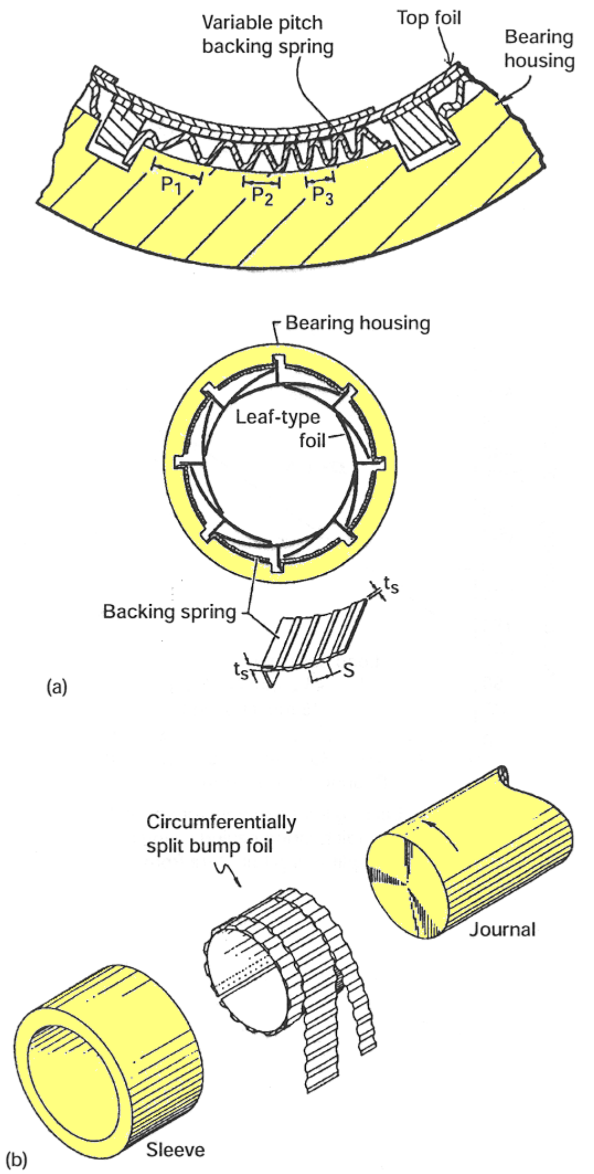

Figure 3 – Generation II foil bearing

turbomachinery applications such as cryogenic turbocompressors and turbopumps. However, their performance (stiffness, damping and load capacity) was insufficient for gas turbines. Several attempts to support small gas turbines using these Generation II bearings were unsuccessful (9, 10). Further, bearings used in gas turbines and APU's encounter high temperatures and the industry standard polymer coatings used to lubricate foil bearings during start-up and shut-down, when surface velocity is too low to develop a lubricating air film, were unsuitable. At that time, no high temperature solid lubricants were available (11).

In the early 1990's, additional advances in bearing design and performance were achieved. The resulting Generation III bearings have more complex elastic spring support structures in which the stiffness is tailored in at least two directions, typically circumferential and axial. These Generation III bearings doubled load capacity over Generation II bearings enabling re-consideration of more challenging gas turbine applications (12, 13). Figure 4 shows the design features of a bump type Generation III foil bearing.

Significant efforts in bearing performance testing, especially at high temperatures has also led to the development of a predictive model for load capacity (6). This Rule-Of-Thumb (ROT) model relates bearing size, speed and design features with load capacity and is expressed in the following equation:

$$W = D_j(DL)(DN)$$

Where:
W is load capacity in pounds
D_j is the bearing load coefficient
D is shaft diameter in inches
L is bearing length in inches
N is shaft speed in thousands of rpm

A similar load capacity ROT has been formulated for thrust foil bearings but has not yet been fully verified experimentally. It is described by the following equation:

$$W = D_t(\pi wD)(DN)$$

Where:
W is load capacity in pounds
D_t is the bearing load coefficient
w is pad width in inches
D is bearing mean diameter in inches
N is shaft speed in thousands of rpm

These ROT models allow the simple estimation of foil bearing performance needed to establish feasibility for a particular shaft

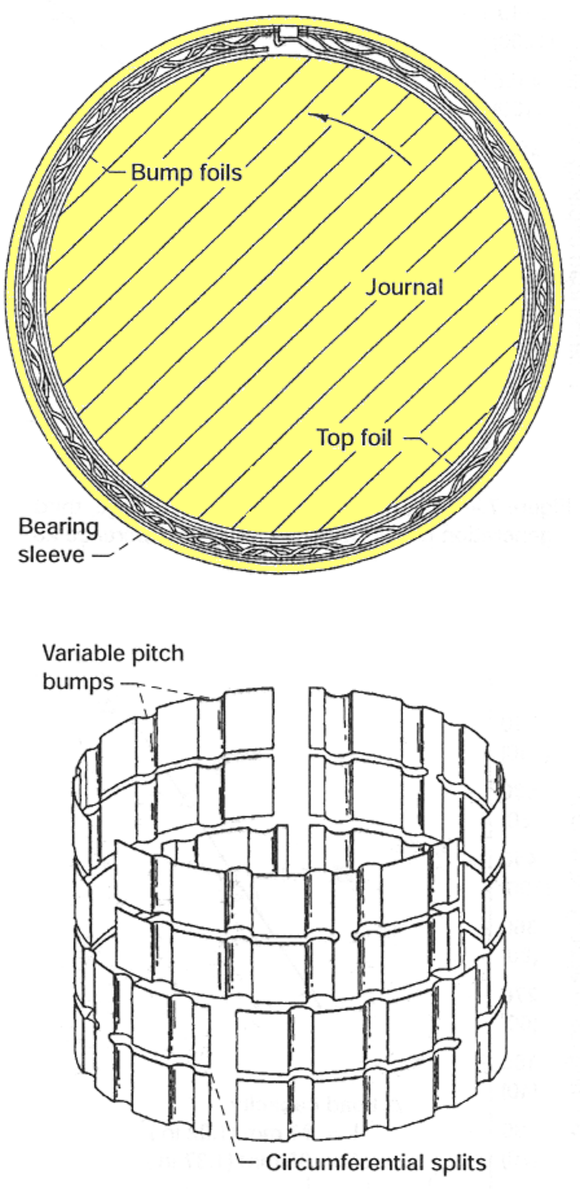

Figure 4 – Generation III foil bearing system. Figure 5 plots the R-O-T for various generation journal bearings.

While much more in-depth study is needed these models are a good starting point for considering Oil-Free technology application. The load capacities of (Generation III) foil air bearings indicate that the technology is capable of supporting small gas turbine engines. Bearings four inches in diameter have supported over one thousand pounds at 22,000 rpm (14). Development work on larger

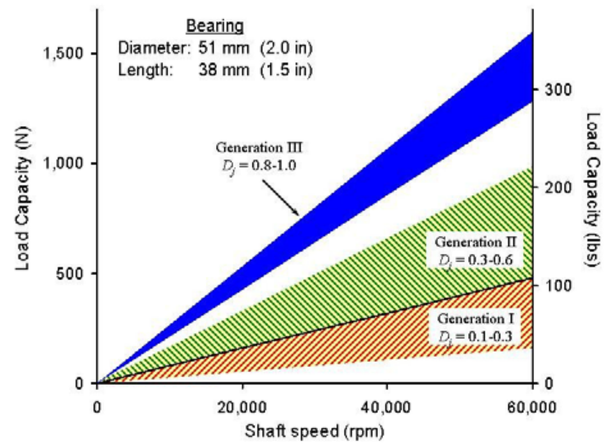

Figure 5 – Load capacity of Generation I, II, and III foil bearings

bearings is underway indicating that the technology may support larger regional jet turbine engines as well.

High Temperature Tribological Coatings

The load capacity models introduced in the previous section and plotted in figure 5 relate specifically to the air lubrication of foil bearings. During initial startup and final coast-down, surface velocities are too low to generate an adequate air film and sliding contact occurs. For these conditions, solid lubrication must be provided to reduce friction and wear. Recent developments in high temperature solid lubrication have shown that long lives at temperatures from ambient to 650 C are possible using advanced shaft lubricant coatings like NASA PS304 (15).

PS304 is a plasma-spray deposited, high temperature, solid lubricant coating specifically developed to lubricate foil air bearings. PS304 is a composite made from a nickel-chromium binder (60 wt%) and chromium oxide hardener (20 wt%) with the solid lubricants silver (10 wt%) and barium/calcium fluoride eutectic (10 wt%). PS304 is deposited onto shaft or runner surfaces which then operate against foil bearings which may also be coated for added wear protection. PS304 has been demonstrated in foil air bearings from

25 to 650 C over a wide range of loads and has provided wear lives in excess of 100,000 start/stop cycles. Table I gives composition and selected properties of PS304 and figure 6 shows a bearing journal after high temperature operation.

TABLE 1 – Composition and Selected Properties of PS304

Constituent / Property	wt%	Function / Value
NiCr[a]	60	matrix-binder
Cr_2O_3	20	hardener phase
Ag	10	low temperature lubricant
BaF_2/CaF_2[b]	10	high temperature lubricant
Thermal expansion CTE	--	$12.4x10^{-6}/^oC$
Density	--	~5.3 g/cc
ρ hardness	--	30 to 34 RC

[a] NiCr ratio is 80/20 by wt%

[b] BaF_2/CaF_2 ratio is 62/38 by wt%

Figure 6 – PS304 coated journal after high temperature start/stop cycles

Recent research has shown that PS304 lubricated foil air bearings require a break-in period before maximum bearing load capacity is realized. During this period surface polishing occurs, making for a more favorable air bearing. In addition, solid lubricants in the PS304 coating form a lubricating glaze on both the coating and foil surface finish, further improving bearing load capacity. Figure 7 shows an x-ray analysis of a PS304 surface after break-in confirming the presence of these lubricants namely Ag, Ca and Ba. Newly developed treatments involving the application of thin sacrificial solid lubricant overlays of graphite have obviated this break-in challenge and resulted in no initial de-rating of foil bearing load capacity. Reference 16 details these developments.

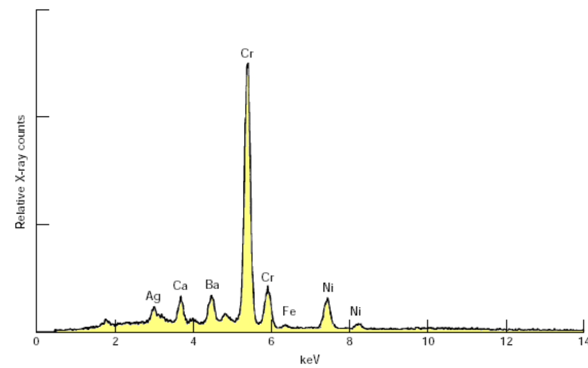

Figure 7 – X-ray analysis of journal surface after break-in

The combination of a suitable high temperature solid lubricant system, like PS304, and advanced high load capacity foil air bearings are key technology enablers for Oil-Free turbomachinery systems. A third key technology is advanced computer based modeling.

Computer Based Modeling

Incorporating foil bearings into high speed, Oil-Free turbomachinery requires that the bearing stiffness, damping and load capacity characteristics are sufficient to control shaft dynamics and operationally and environmentally imposed loads (17). Previous attempts to utilize foil air bearings relied mainly on a build and test approach to ascertain whether the bearing characteristics were adequate to ensure rotordynamically stable operation. This type of approach can be expensive and carries high risk of failure. Also, if hardware failure occurs it can be difficult to assess the root cause without an analytical understanding of the rotating system and its predicted characteristics (18).

New computer based, finite element rotordynamic modeling techniques can be used to minimize the need for build and test efforts. This can greatly enhance the chances for successful system operation and help avoid iterative design and test efforts. Computer based modeling of thermal and centrifugal stresses, hydrodynamic modeling of the lubricating fluid film and even elastic modeling of the foil bearing structure can aid in the understanding of rotor system performance before any hardware is made. Computer based models of foil bearing supported rotors is, however, an ongoing activity. While thermal stress and distortion and mechanical stress models are well-developed, hydrodynamic modeling and modeling of complex elastically supported non-linear foil bearings are not. Further, the interactions between foil bearing dynamic characteristics, load capacity and power loss and turbomachinery systems such as secondary airflow and thermal management have not been fully explored.

Current Technology Application and Future Capabilities

The successful application of Oil-Free technologies (foil bearings, solid lubricants, and modeling) to turbomachiney systems requires the concurrent development of these three key technologies coupled with timely and appropriate technology demonstrations. These demonstrations provide vital experimental feedback and corroboration to the research effort. Demonstrations also highlight critical research areas that may need more investigation. Also, demonstrations often lead to new products and other applications are critical in developing an industrial base for technology commercialization.

The successful commercialization of foil bearings in Oil-Free Air Cycle Machines (ACM's) in the 1970's represented the first transition of foil bearings from laboratory into the field. These ACM's utilized then state-of-the-art Generation I foil bearings combined with polymer (PTFE) solid lubricant coatings to provide Oil-Free rotor support. Shaft speeds were moderate (~40,000 rpm) and ambient temperatures were less than 200 C. These early Oil-Free turbomachines eliminated oil mist in the cabin of aircraft and, over the years, accumulated impressive statistics of reliability and mean-time between failures in excess of 100,000 hrs. In fact, foil bearing supported ACM's have been the industry standard in new aircraft since the 1980's (5,19).

Based upon the technical and commercial success of the first ACM's, demonstrations of foil bearing supported small gas turbines were attempted first in the late 1970's then again in the mid 1980's. These engine demonstrations employed newly developed Generation II foil air bearings and then state-of-the-art solid lubricants capable of operating at temperatures to 300 C. Unfortunately, only relatively primitive thermal and mechanical (and rotordynamic) modeling techniques were available to guide the design process. Further, the rudimentary foil bearing performance prediction models were little better than guessing. These projects were not fully successful (10,18).

In some cases the bearing load capacity was insufficient to support the dynamic loads. In other cases, the solid lubricants wore too quickly. Oftentimes, a combination of marginal bearing performance characteristics leads to failure. For example, if a bearing has little or no margin on load capacity it cannot accommodate even slightly higher than anticipated misalignment levels. However, excess load capacity may allow a bearing to handle extra imbalance forces, increased preload or even excessive shaft or foil wear.

In several engine demonstration projects, the rotor system could be run using the foil bearings but failure occurred under certain operating conditions (e.g. under full power or dynamic shock). Nonetheless, the engine demonstration projects undertaken in the 1970's and 1980's suffered primarily from insufficient bearing load capacity and damping and secondarily from inadequate high temperature solid lubricants. These shortcomings dampened interest in Oil-Free gas turbines for nearly a decade (18).

In 1991, Heshmat reported a doubling of foil bearing load capacity through judicious design of the foil bearing elastic support structure (20). In his design, the stiffness of the structure is tailored both circumferentially and axially to optimize the formation of the fluid film and minimize leakage. Following his development, other researchers reported similar gains using slightly varied designs. These improved performance bearings encouraged a resurrection of the Oil-Free engine concept. In addition, the concurrent development of widely available, computer based modeling techniques made the virtual design of such an Oil-Free engine possible.

One application enabled by the development of high load capacity foil bearings and high temperature solid lubricants, like PS304 is an Oil-Free turbocharger. In 1995, NASA and the Department of Energy teamed with industry to demonstrate a 150 hp Oil-Free turbocharger for a heavy-duty diesel engine. The resulting turbocharger, shown in figure 8, incorporated two journal and a double acting thrust foil bearing and ran successfully at 95,000 rpm and 650 C turbine temperature in early 1999 (21). The Oil-Free turbocharger verified the successful demonstration approach outlined by Valco (22) which includes a four step iterative process. The first step is a feasibility study followed by bearing design and testing. This is followed by testing of a foil bearing supported simulated rotor system (matching rotor system masses and inertias rotordynamically but not the aerodynamic loads). The final step is a full system technology demonstration test.

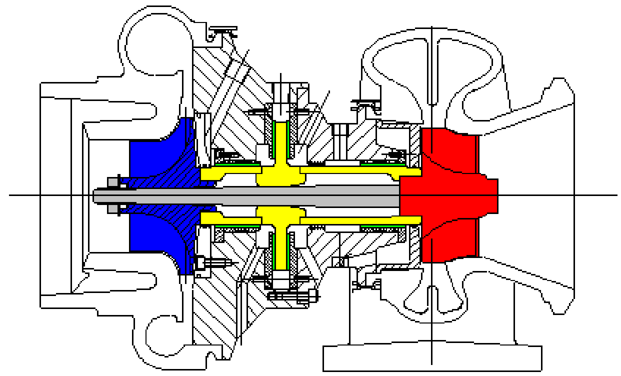

Figure 8 – Oil-Free turbocharger

Among the earliest attempts to build a successful small Oil-Free gas turbine was the 30 kW Capstone microturbine. This recuperated turbine-generator system was originally conceived as a power plant for a hybrid turbine-electric automotive propulsion system. Although the resulting microturbine was deemed economically unviable for the automotive market it is technically successful. Figure 9 shows a cross section of the Capstone 30 kW engine which was brought to the market as a stationary power generator in 1999. Since then, over 2500 units have been sold in both 30 kW and 60 kW versions. A 200 kW machine is currently under development. The Capstone Microturbine holds the distinction of being the world's first commercially available Oil-Free gas turbine.

The Capstone microturbine employs patented foil air bearings (23). Patent drawings indicate that these bearings are highly complex yet simple to produce and are categorized as Generation III bearings. They use a proprietary foil coating in their production model. In a collaborative effort with NASA, the PS304 coating has been successfully tested in the Capstone engine to acquire early gas

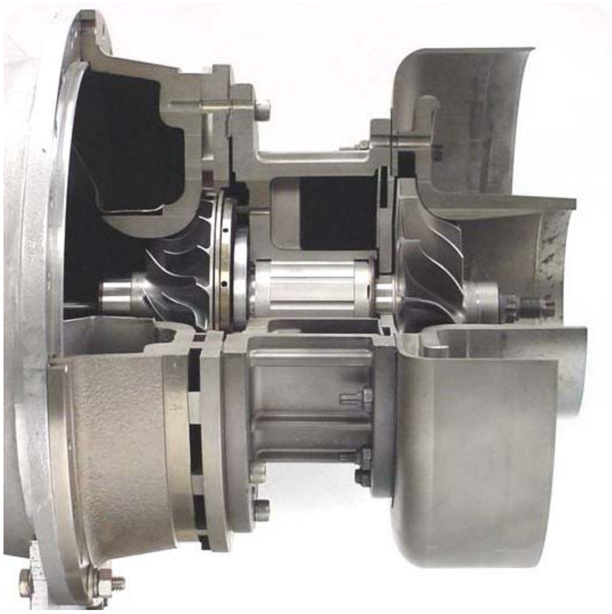

Figure 9 – Oil-Free engine for 30 kW microturbine

turbine environmental experience prior to using the technology in aircraft engines.

Another turbine company, Honeywell, developed a competing product to the Capstone microturbine but never went beyond the field demonstration stage. Honeywell's 75 kW Parallon utilized cooled foil bearings and conventional polymer solid lubricants which are similar to technology found in their air cycle machines (ACM's). These generating units accumulated substantial operating time but did not enter commercial production.

Beyond terrestrial power generation, there is considerable interest in developing Oil-Free turbine engines for aeropropulsion and power applications. For instance, NASA Glenn is investigating the application of foil air bearings and high temperature solid lubricant coatings to the Williams International EJ-22, 700 lb thrust business jet turbofan engine (23). Preliminary design has been completed. The analytical results and early results from individual bearing component tests show that supporting the core on foil air bearings is feasible. Further tests are underway using simulated rotors to study shaft dynamics and bearing interactions for an Oil-Free core shaft. Although future funding for the continuation of this project has not yet been secured, the technical results are promising.

Recently, industry has announced successful tests of a radial hot section foil bearing in a 225 kW (300 lbs thrust) drone class turbojet engine (24). This engine used a fuel lubricated rolling element bearing in the cold section and a radial foil air bearing in its hot section. A photograph of the engine hardware is shown in figure 10. The engine operated over its entire range of speeds and thrust levels and adds confidence that small turbine engines are excellent applications for Oil-Free technology.

Figure 10 – Test hardware for a turbojet with hot section foil bearing

In addition, the encouraging results suggest that larger rotor system could be supported using Oil-Free technologies including larger Regional Jet engines and even Supersonic Business Jet engines. For these applications the system benefits go beyond those realized by removal of the oil system.

In a commercial regional jet engine, it has been estimated that 15% of the engine weight and 50% of the maintenance costs can be attributed to the oil system (25). Further, an Oil-Free engine utilizing an integral start generator (ISG) eliminating the need for an oil-lubricated, accessory gearbox, would have a smaller overall (under nacelle) diameter leading to reduced aerodynamic drag. The airframe would also benefit because the reduced engine weight requires lighter structural elements between the engine and the airframe resulting in lower aircraft weight. This cascading effect could also be realized in operational costs. Removing oil, oil filters and sensors from the maintenance logistics stream reduces operator costs beyond just the engine.

The load capacity model presented earlier suggests that two six inch diameter bearings operating at 20,000 rpm can support over 4000 pounds of radial load. This would exceed a sustained 20g load on a 200 pound rotor that is representative of the core of a 5000 pound thrust engine. For this type of application, thrust load management remains a design concern. The size, rotating inertia and excessive frictional (power) losses associated with a 5000 pound thrust bearing would be untenable. For an Oil-Free regional jet class engine, a design goal would be to judiciously use secondary airflows and cavity pressures to minimize aerodynamically derived thrust loads from the engine. Unlike rolling element bearings that require thrust preloads to prevent ball skidding during transients, foil air bearings do not need a preload. In fact, on a unit area basis, thrust foil air bearings have much lower thrust load capacity than ball bearings even at high speeds. To prevent thrust bearing overloads and reduce frictional losses, engine shaft thrust load management is critical. Further, frictional heat generating in the lubricating gas film must be removed making secondary airflow design, pressure balancing and cavity purging an important systems issue. The technical success of the Capstone and Parallon turbines show that this type of design is feasible.

For rotorcraft propulsion applications, the engine must be configured to drive a low speed main rotor. This is accomplished through a speed reduction gearbox (transmission). Since the contact area between meshing gear teeth is a heavily loaded, gear teeth require liquid lubricants (oil). Therefore a rotorcraft propulsion system can not be completely Oil-Free. However by utilizing a coupling between the engine and the gearbox or incorporating an aerodynamically coupled power turbine an Oil-Free engine can still be used. This will result in reduced weight and maintenance compared to a conventional engine. Weight reduction in rotorcraft applications provide more significant vehicle benefits than fixed wing aircraft. This provides compelling reasons to pursue Oil-Free technology for these applications.

For supersonic flight vehicles, there is an additional benefit of utilizing Oil-Free turbines. That is the elimination of the need to provide cooling for the oil lubricants. In conventional subsonic systems, oil cooling is readily accomplished with direct air heat exchangers. In supersonic flight vehicles, however, ram air heating of the slip stream makes oil system heat rejection directly to the environment impossible. Active oil cooling using main engine bleed air coolers or ACM’s can provide a solution albeit at the expense of system weight and complexity and energy consumption.

Another option is to reject oil heat into the fuel prior to combustion, thereby using the fuel as a heat sink. This approach has been used successfully in military aircraft which undergo short duration supersonic sorties preceded and followed by subsonic cruising. In a supersonic business jet application, however, the thermal sink capacity of the fuel is limited. Significant aerodynamic skin friction heating of the airframe generates a large demand on the use of fuel cooling. In addition, numerous electronic and electrical components also rely on the fuel as a heat sink.

For sustained supersonic flights the fuel required for propulsion is significantly less than that required for thermal management and cooling. This heat sink "shortage" is exacerbated by adding the heat rejection from the lubricating oil. One solution is to carry more fuel than is needed for the mission. But carrying extra fuel adds unnecessary weight and volume to the aircraft effectively reducing useable payload. Elimination of the oil system and the need for oil cooling can contribute to major weight and system complexity savings for a supersonic flight vehicle.

Foil air bearing supported engines can tolerate bearing compartment temperatures as high as 650 C. This current temperature limit is the maximum use temperature for the nickel base superalloy used to make the foil spring elements. Above 700 C these critical foil properties quickly degrade and can hinder bearing performance. Recent research indicates that bearings can be designed to accommodate the reduced modulus of superalloys at these high temperatures. Ongoing work on high temperature bearings and the consideration of cobalt based alloys with higher temperature capability may push foil bearing operating limits to as high as 800 C. Nonetheless, foil bearing temperatures of 650 C preclude the need for elaborate cooling mechanisms. The minimal heat generated in foil bearings, due to the viscous shear of the thin lubricating gas film, is readily managed using small amounts of bleed air or even direct cooling to the slip stream (estimated at around 350 C). Since the structural components (turbine disks, shafting, etc.) must be maintained at temperatures at or below 650 C to ensure adequate strength and life foil bearings will not require or introduce any unusual or technically challenging thermal management system.

Summary Remarks

These system examples highlight some of the benefits Oil-Free technologies can have on aerospace propulsion systems. Table II summarizes the system benefits of replacing traditional oil-lubricated rotor supports with Oil-Free technologies. Significant reductions in engine weight and maintenance costs are among the main benefits.

TABLE II – System Benefit Summary

Engine Application Benefit Impact Level

System Benefit	Regional Jet	Rotor-craft	Supersonic Business Jet
Weight reduction	medium	high	high
Maintenance reduction	high	high	medium
Heat rejection	low	low	high
Engine frontal area / drag reduction	medium	low	high

While the obvious advantages are clear, more subtle enhancements are possible when the engine rotor support system is changed to one in which speed limitations are removed. Further, using bearings which do not require oil supply and return piping can allow structural efficiencies in engine design. These changes can have a positive effect on flow path areas and restrictions as well.

When these system benefits are coupled with a specific mission profile characteristics the reasons to replace conventional technology with Oil-Free technologies becomes even more compelling. For example, on rotorcraft, especially small ones, weight savings are critical and Oil-

Free engines can reduce weight by 15%. Further, by elimination of the need for engine oil, an optimized gearbox oil system can be employed with additional performance benefits. For regional jets, the maintenance cost savings realized by removing the oil system can translate into Direct Operating Cost reductions which dwarf even major improvements in specific fuel consumption. For supersonic flight, weight and maintenance cost improvements which benefit rotorcraft and regional jets also apply. However, the elimination of oil and the need for active oil cooling can be the enabling key to a deployable supersonic business jet capable of sustained supersonic cruise at manageable cost.

Research in performance estimation and prediction indicates that the technology is ready for demonstration in small propulsion turbines. As analytical and experimental progress in Oil-Free technologies is made, larger and more demanding propulsion applications are possible. Oil-Free technologies have enjoyed full acceptance in air cycle machines and turbocompressor applications. The technical success of small foil bearing supported turbine generators and the advances described in this paper help ensure that Oil-Free engines have a bright future in aerospace propulsion.

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